Fast-ion energy loss during TAE avalanches in NSTX*

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NSTX-U

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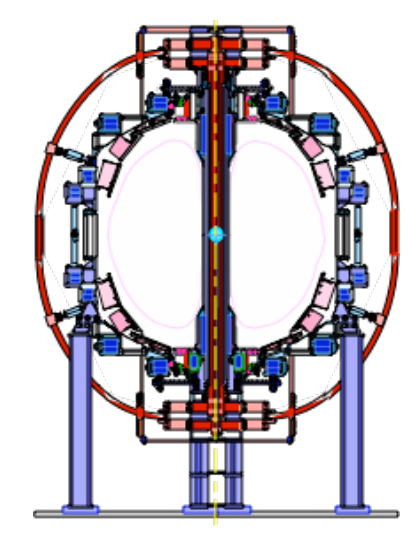
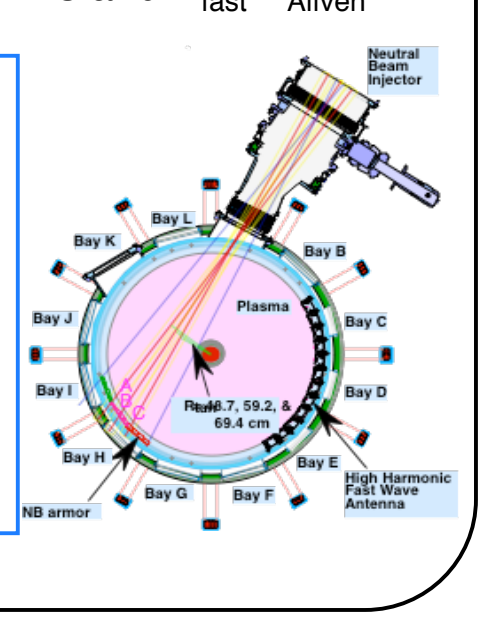
NSTX has low field, high density and current; perfect for study of fast ion-driven modes

- Low field, high density $V_{Alfvén} \approx 0.5 - 2.7 \times 10^6$ m/s.
- Beam injection energy 60 - 100 kV, $V_{fast} \approx 2.6 - 3.1 \times 10^6$ m/s
- Reactors would have higher field, fusion α's and $V_{fast}/V_{Alfvén} > 1$

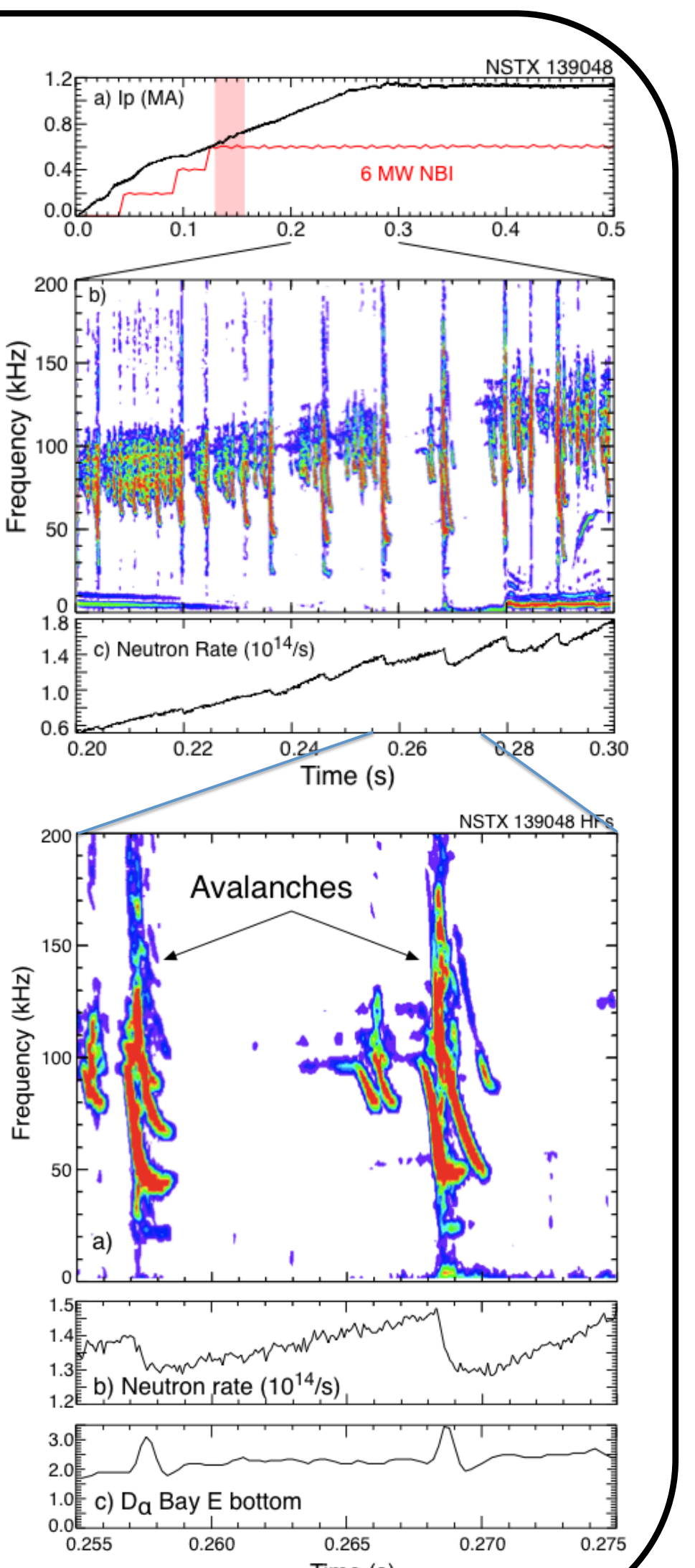


$R_0 = 0.86$ m
$a = 0.68$ m
$B_0 = 0.3\text{-}0.55$ T
$I_p \leq 1.2$ MA
$\beta_{tor} \leq 40\%$
$n_e \leq 1 \times 10^{20}/m^3$



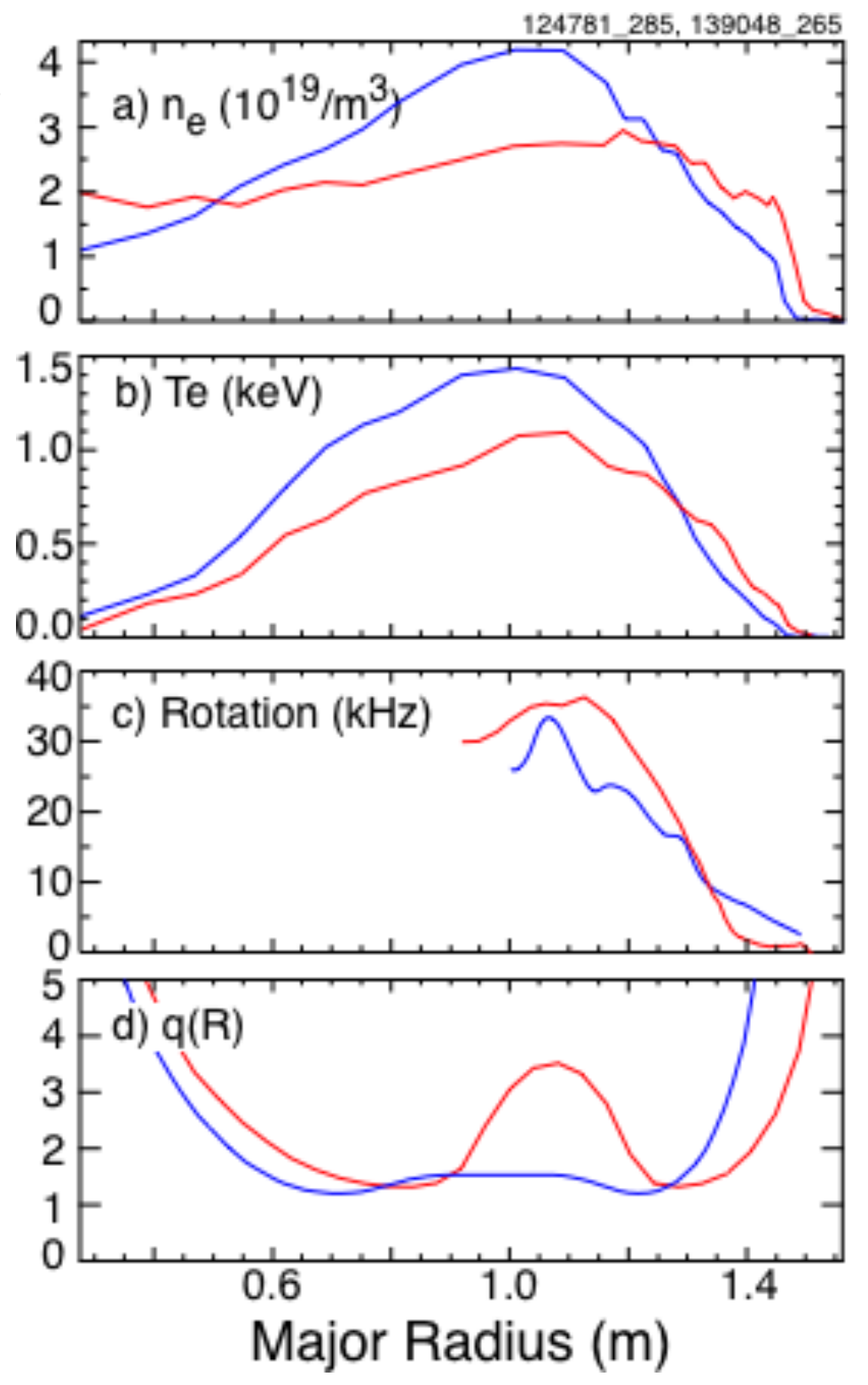
Simulations find neutron drop due to redistribution, loss of fast ion energy, not fast ion losses

- Drops in neutron rate of up to 15% are seen co-incident with TAE avalanche bursts, implying fast ion losses.
- ORBIT simulations of fast ion redistribution using NOVA eigenmodes and experimental measurements of mode amplitude and frequency chirping found fast ion losses were small.
- At measured mode amplitudes there was a decrease in energy in the ORBIT sample fast ion population.
- This drop in fast ion energy, together with some internal redistribution, could account for the neutron rate drop.
- The estimated loss in fast ion energy is roughly comparable to estimates of energy transferred to thermal population through damping of the TAE.



This analysis done on TAE avalanches in H-mode plasmas with reflectometer data

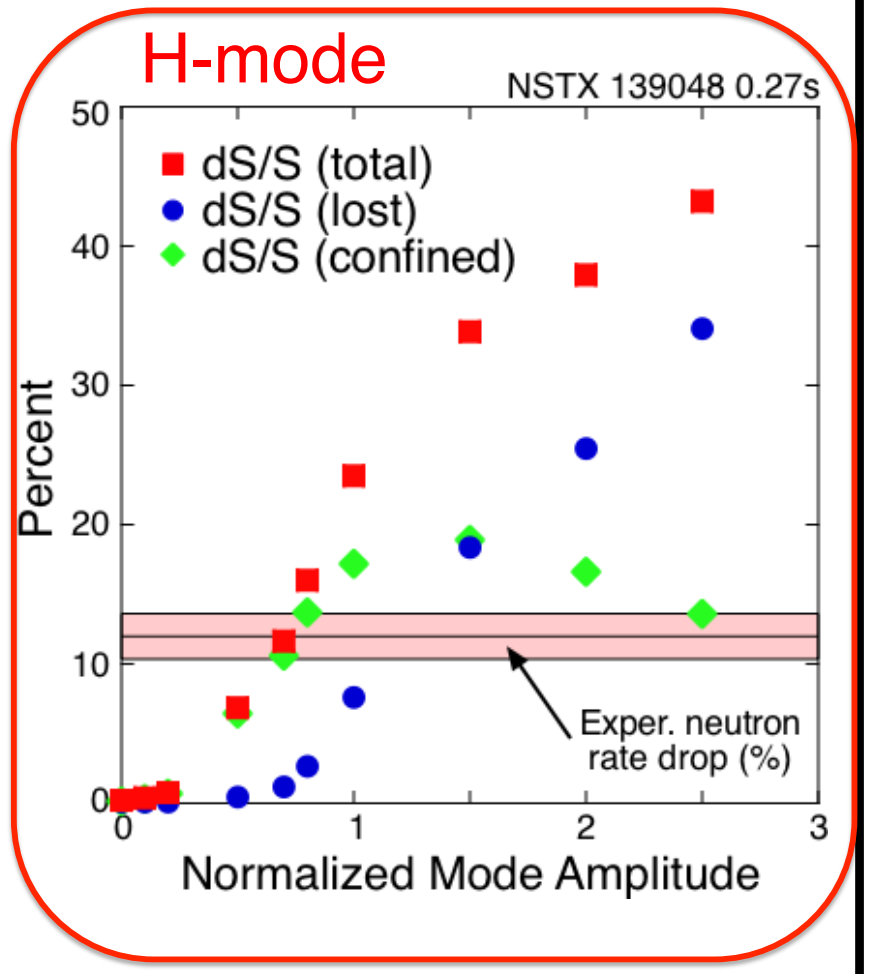
- Analysis requires internal measurements of TAE amplitude, thus density profile must be peaked.
- Initial studies of TAE avalanche affect on fast ions used L-mode plasmas with peaked density profiles.
- Most H-mode density profiles flat in early phase, but some H-modes have some weak density peaking in core.
- Both H-mode and L-mode plasmas had strong, sheared toroidal rotation; mixes TAE frequency with core MHD frequency.
- TAE avalanches also seem correlated with shear reversal in core.
- H-mode avalanches seen with full energy beams (90 keV), but in L-mode needed lower energy beams (70 keV).

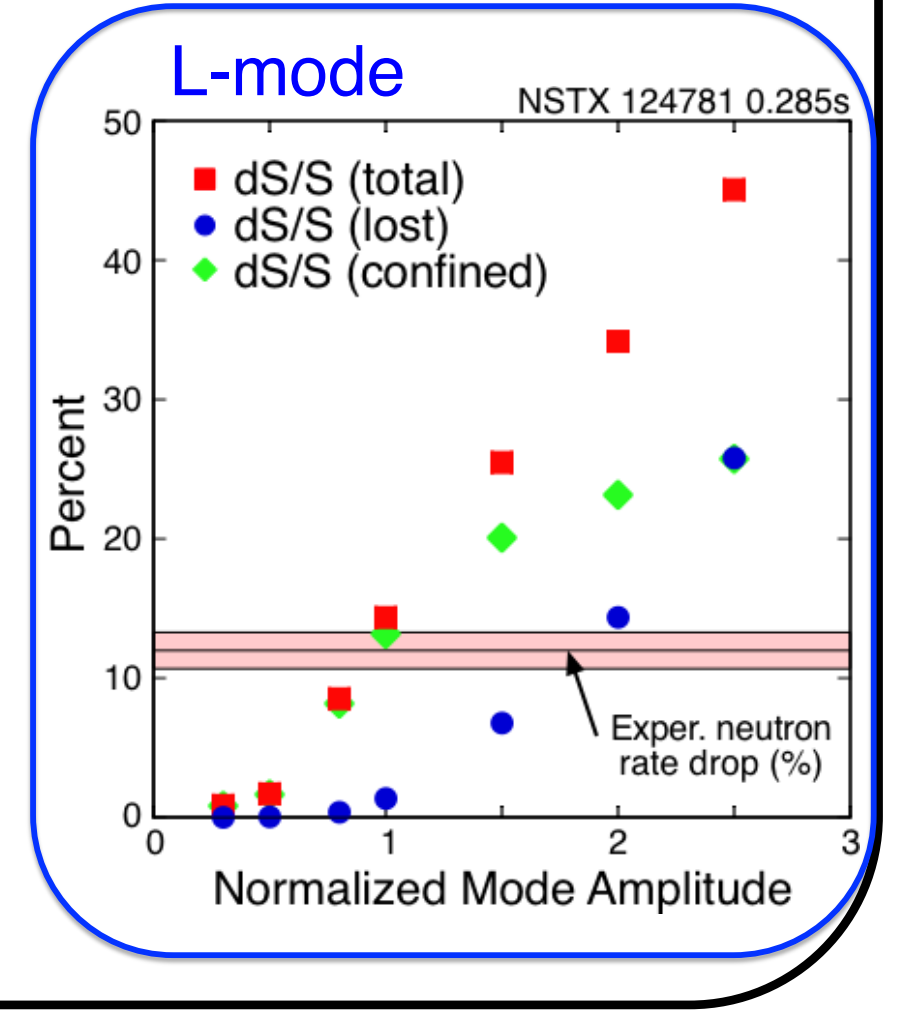


- H-mode data shown in red here, and red boxes elsewhere
- L-mode data shown in blue.

Apparent stochastic transport onset seen in ORBIT simulations

- The red squares show the estimated total neutron rate drop vs. scaled TAE amplitude.
- Threshold is seen for onset of significant neutron rate drop in ORBIT simulations (at ≈ 0.3 of nominal measured mode amplitude).
- Neutron rate drop at low amplitude primarily from energy loss and some from redistribution.
- In H-mode neutron rate drop due to fast ion losses onsets at ≈0.7 of nominal mode amplitude (blue circles).
- In L-mode neutron rate drop due to fast ion losses onsets at ≈ nominal mode amplitude (blue circles).

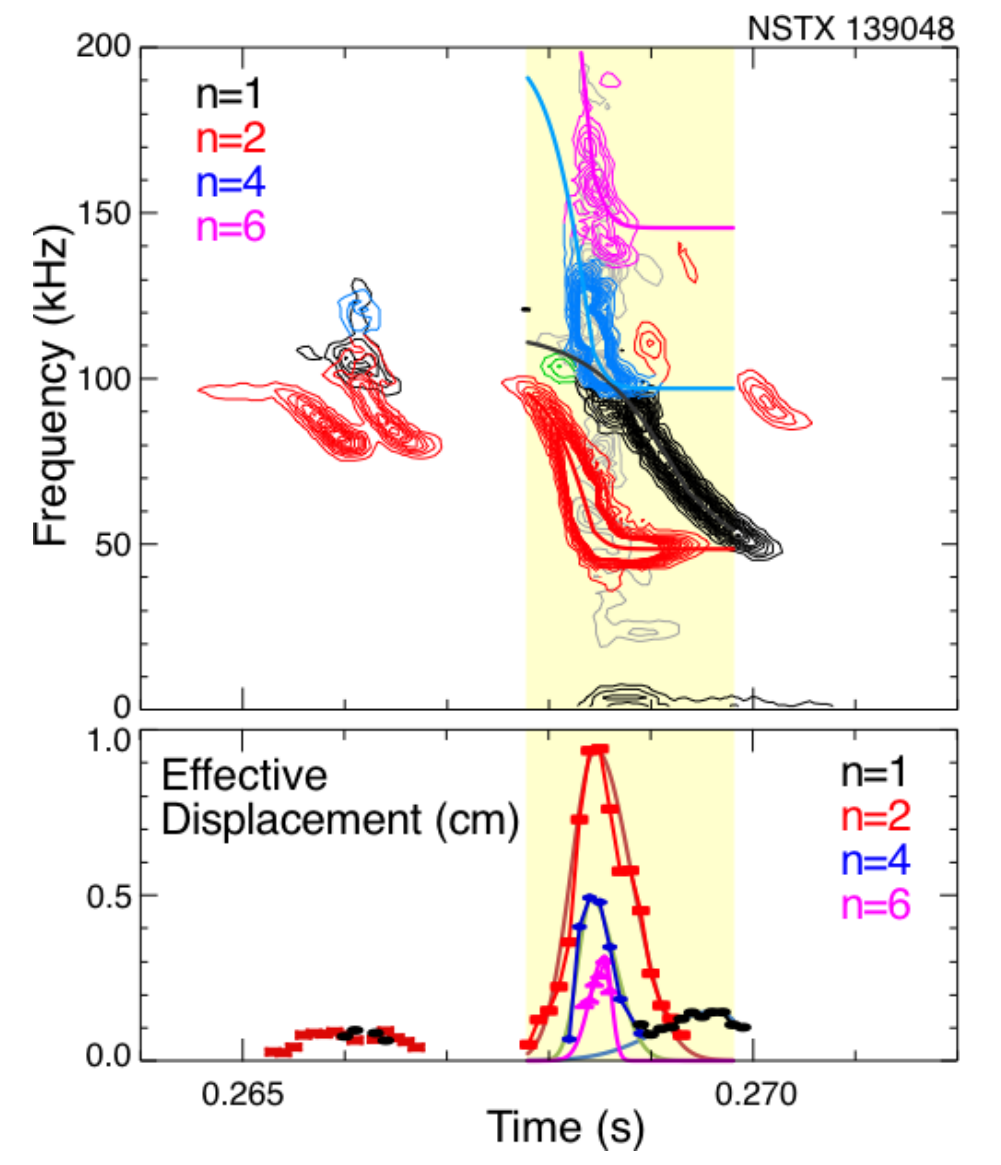




NOVA and ORBIT capture physics of TAE avalanches

- Amplitudes of Toroidal Alfvén Eigenmodes have been measured with reflectometer array
- Ideal mode structure is calculated with NOVA linear code.
- NOVA ideal modes, scaled to experimental amplitude, used in ORBIT to simulate affect on fast ion population.
- Up to the measured mode amplitude, dominant effect is a reduction in net energy of the sample fast ion population.
- Reduction in fast ion energy reduces fusion rate; drop is consistent with experimental drop in neutron rate.
- Simulated energy lost from fast ions is comparable to estimated energy lost to TAE damping.

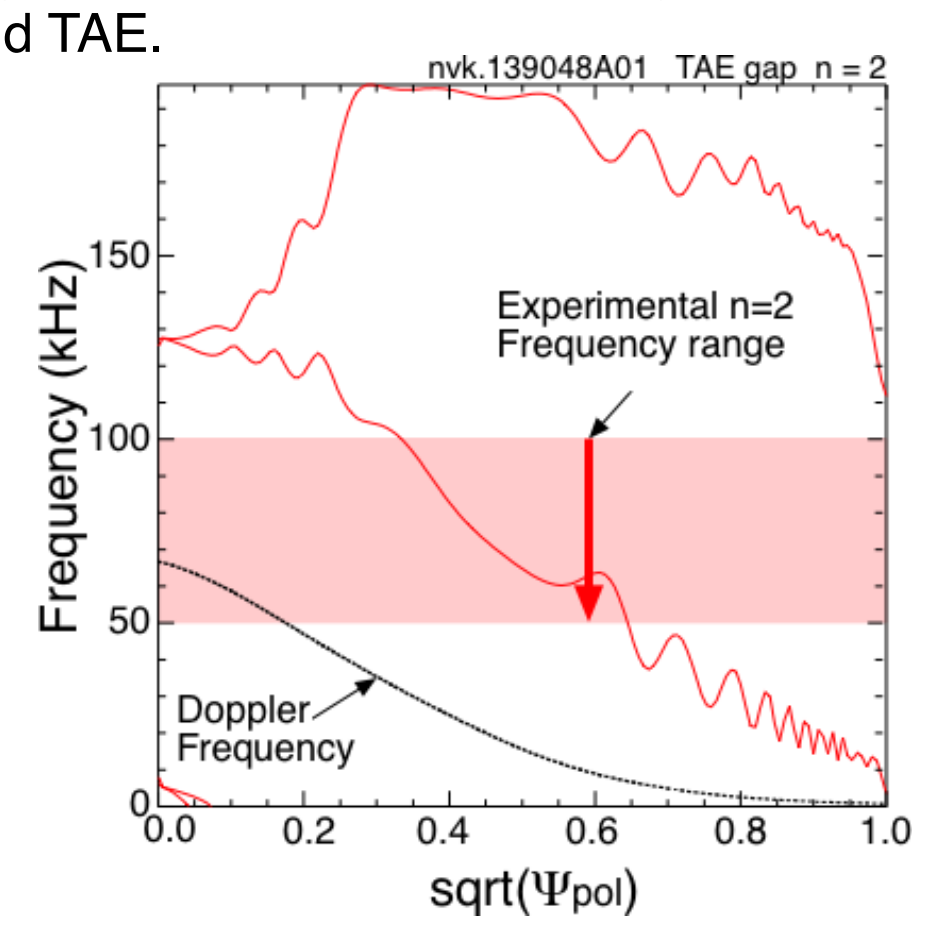
Four dominant modes present in H-mode TAE avalanche burst



- Analytic fits to the frequency and mode amplitude evolution are used in ORBIT
- the peak mode amplitude evolution for each mode from the reflectometer array.

Strong sheared rotation typically closes TAE gaps

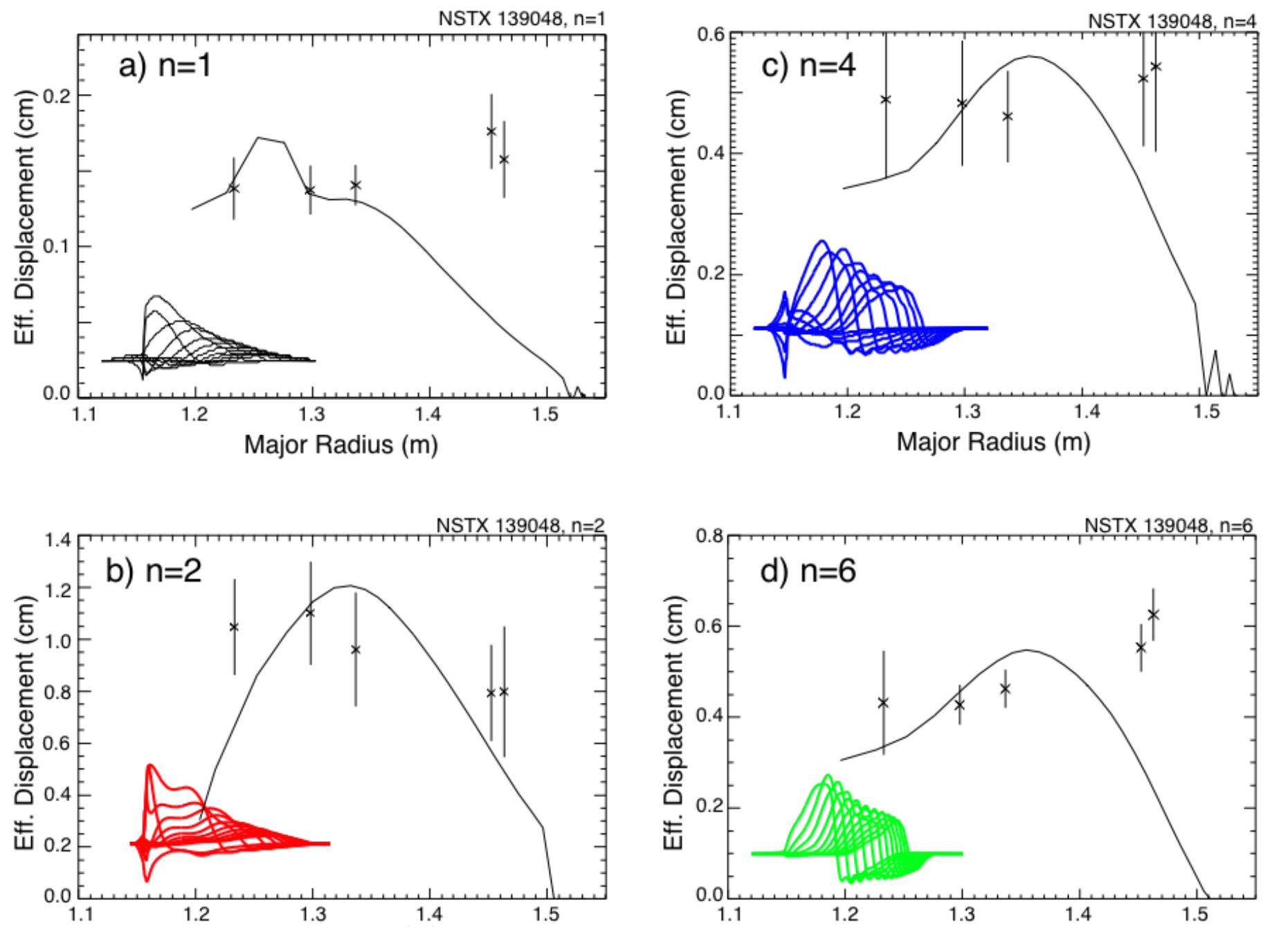
- TAE frequency close to kink frequency in core region – could lead to coupling between MHD and TAE.



- The continuum structure for the n=2 TAE is strongly distorted by the sheared rotation profile; first-order corrections introduced in NOVA (G. Kramer).
- Red band shows range of the n=2 TAE frequency chirp.

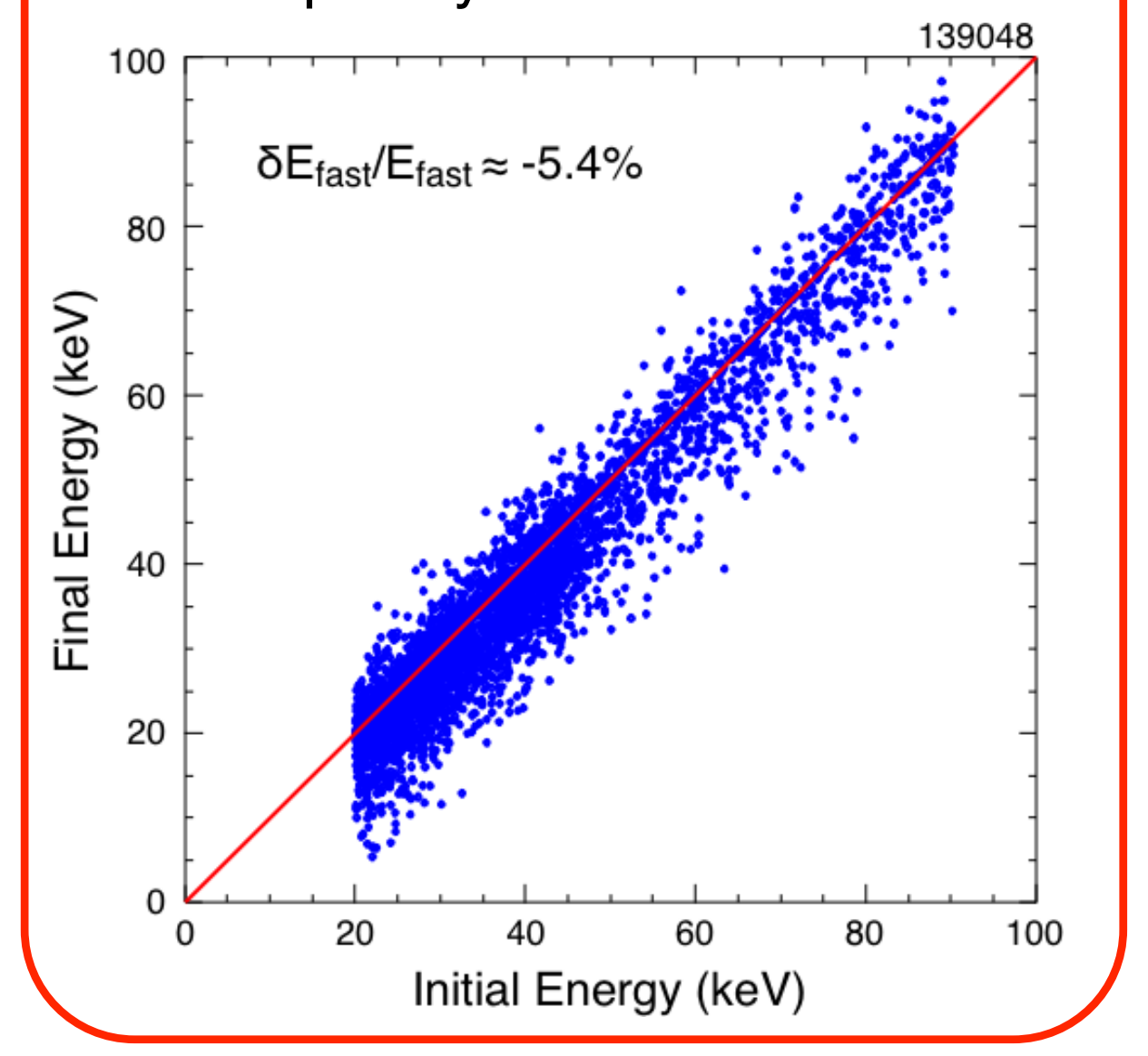
The simulated reflectometer response using NOVA eigenmodes is fit to the mode amplitude measured with reflectometer array

- Solid curves are simulated reflectometer response to be compared with reflectometer data.
- Black points are reflectometer data from five of the twelve channel array.
- Reflectometer measurement location mapped using Thomson scattering density profile (with some smoothing).
- Insets show NOVA poloidal harmonics for modes.

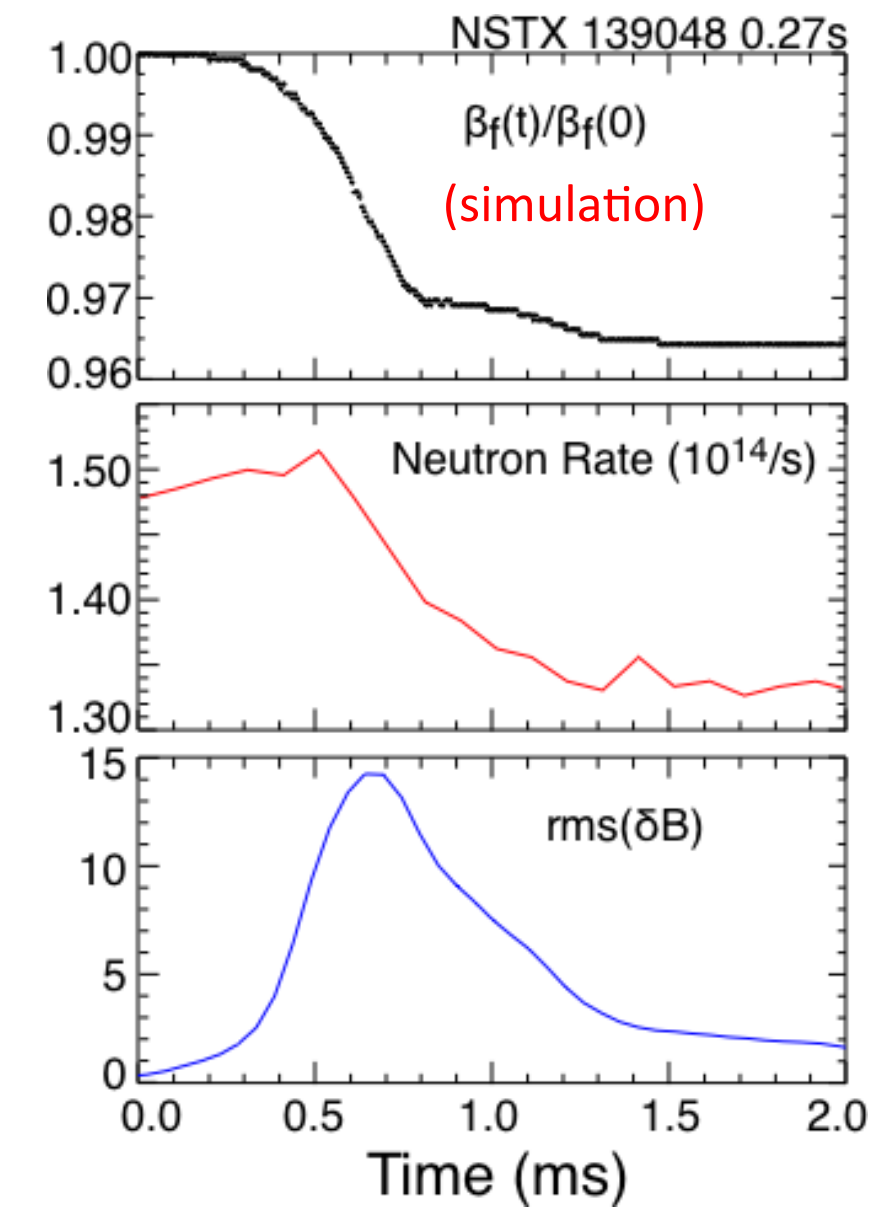


Fast ion population has an ≈5% drop in energy through avalanche

- Initial and final beam ion energies for an ORBIT avalanche simulation using measured mode amplitude and frequency evolutions.



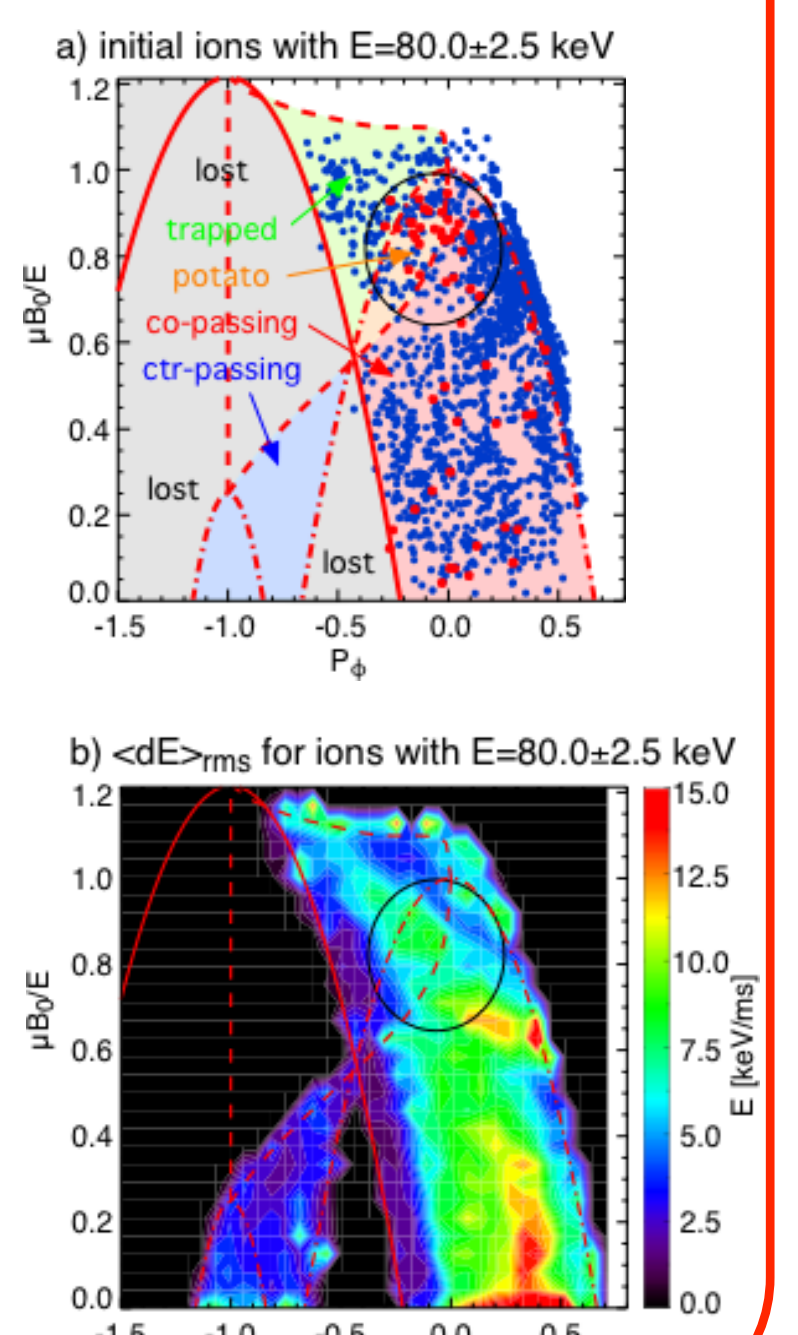
ORBIT $\delta\beta_{fast}$ decay time consistent with measured δS



- Evolution of experimental neutron rate (middle panel),
- and growth of TAE (last panel).

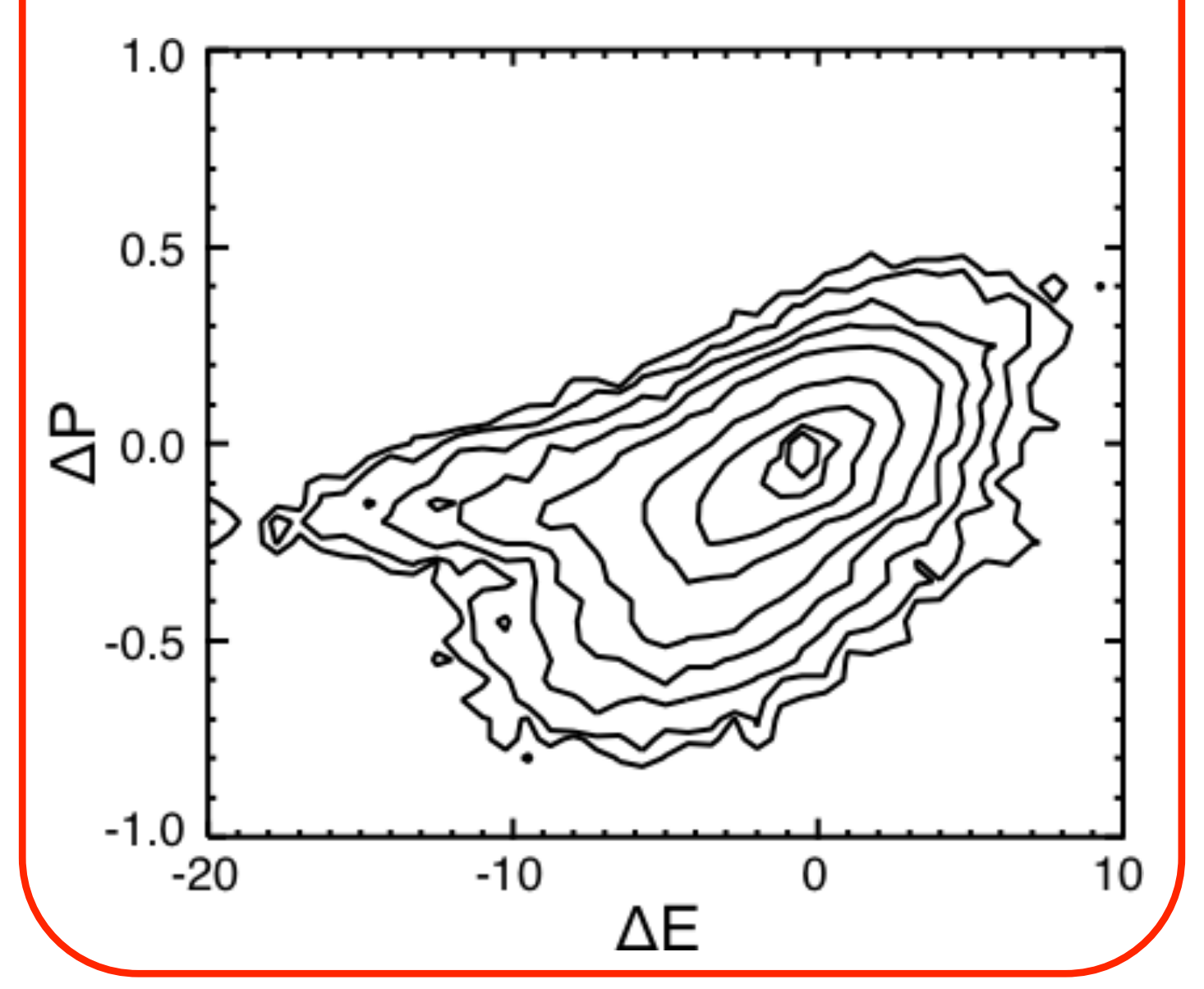
ORBIT can be used to identify classes of fast ions interacting with TAE

- Initial distribution of fast ions with 78.5 keV ≤ E_0 ≤ 82.5 keV - those in red are lost in avalanche.
- This diagram classifies fast ions in terms of orbit type, as indicated.
- rms fluctuation in energy for isotropic distribution of fast ions; stronger fluctuations (red) indicate stronger interaction with the modes.



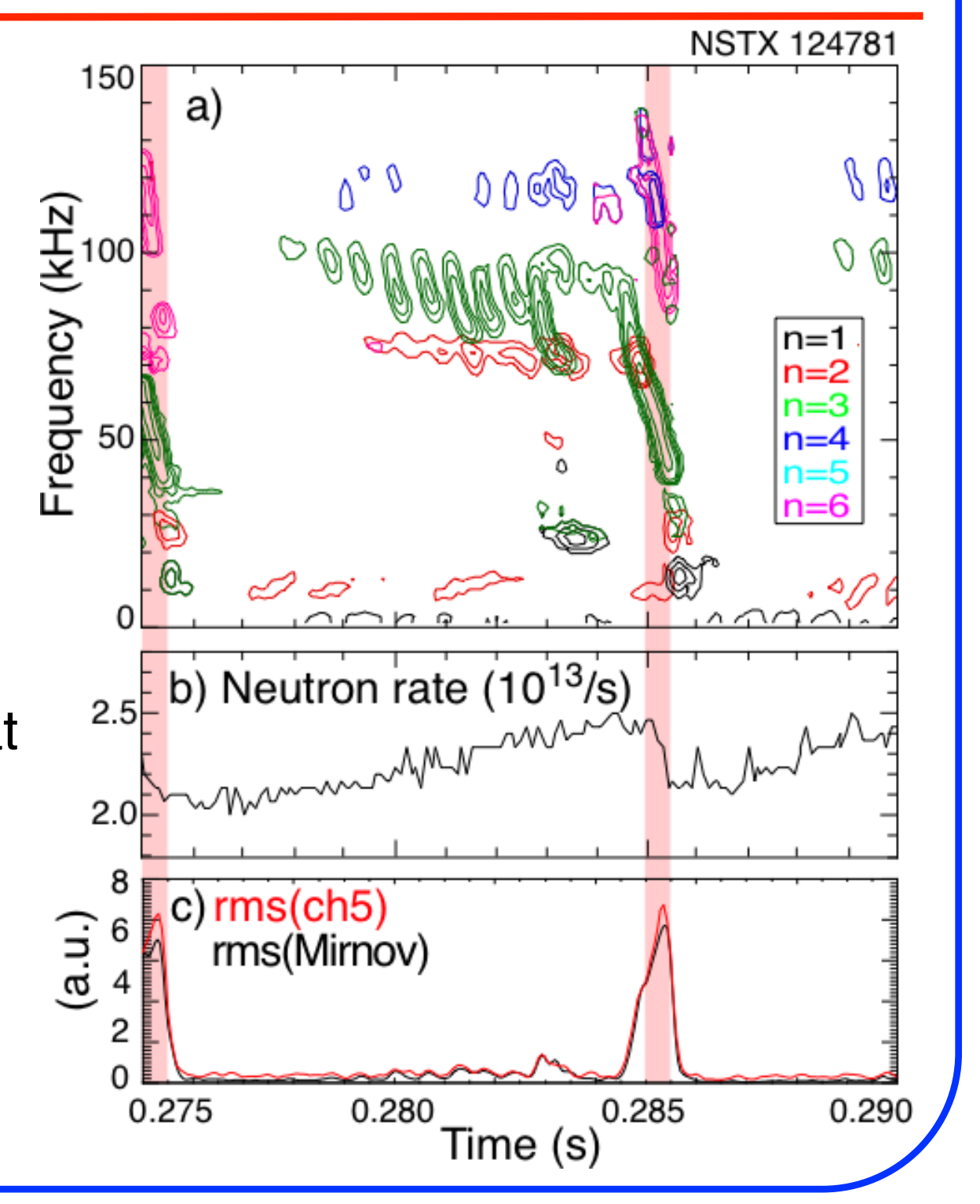
Even with multiple n's, frequency chirping, *nE - ωP* ≈ constant

- Contour plot of the density of fast ions vs. change in canonical angular momentum (ΔP) and change in energy (ΔE).



Similar NOVA/ORBIT analysis is also done for **L-mode** avalanche example

- Avalanche burst lasted longer in L-mode plasmas, 2 ms vs. 1ms.
- Similar number of modes, but dominant mode number is higher with n=3 *vs.* n=2.
- Both L-mode and H-mode had strong frequency chirps.
- Neutron drop was comparable at a bit more than 10% drop.
- Both L-mode and H-mode had reversed core magnetic shear during avalanching.



Agreement between NOVA eigenmode shapes and measured L-mode mode profiles is better

- Modes are generally more core-localized than in H-mode.
- Better fit to reflectometer data possibly because peaked profile measurements are better.
- Mode amplitude somewhat larger in L-mode, peak amplitude of largest mode is 13% vs. 7.5% in H-mode.